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APPARATUS AND METHOD FOR OPTIMIZING THE POWER TRANSFER

PRODUCED BY A WAVE ENERGY CONVERTER (WEC)

BACKGROUND OF THE INVENTION

This application claims priority based on a previously filed provisional application titled "APPARATUS AND METHOD FOR OPTIMIZING THE POWER TRANSFER PRODUCED BY A WAVE ENERGY CONVERTER (WEC)" filed on 8/7/00 and bearing serial number S/N 60/223132,

This invention relates to the conversion of energy from naturally occurring sources of mechanical energy , such as the mechanical energy present in ocean surface waves, to electrical energy and, in particular, to the efficient production and transfer of that energy.

Various wave energy converter (WEC) systems are known. For example, reference is made to U.S. patent application S/N 09/379,421 filed August 21, 1999, titled "Wave Energy Converter Utilizing Pressure Differences", assigned to the assignee of the present application and the teachings of which are incorporated herein by reference.

Numerous problems exist in the design of a mechanical system for harnessing the energy contained in ocean waves. Particularly, a problem exists in harnessing this energy efficiently. In addition, there is a further problem of converting the mechanical energy into electrical energy in an efficient manner. A significant difficulty in increasing the efficiency of converting the ocean wave

energy into electric energy is due to the fact that the waves vary continuously in amplitude, frequency and phase as function of time.

SUMMARY OF THE INVENTION

Applicants' invention resides, in part, in the recognition that certain parameters and components need to be controlled to optimize the power transfer. Applicants' invention also resides in the recognition that a power generating mechanical system may be characterized as an effective capacitive (or inductive) element and that an inductive (or capacitive) element may be added to the system to resonate with the effective capacitance (inductance) of the mechanical system to increase the efficiency of the power transfer. Accordingly, systems embodying the invention include inductive (or capacitive) elements tending to cause resonance with the effective capacitance (inductance) of the power generating mechanical system in order to increase the efficiency of the system.

Applicants' invention also resides in the recognition that the load coupled to the system has an optimum value and in setting the load to such a value to increase the power transfer and the efficiency of the system.

Applicants' invention also resides in the recognition that the effective capacitance (inductance) of a mechanical energy converter system varies as a function of the frequency of the ocean waves. Accordingly, systems embodying the invention may include a controller responsive to the frequency of the ocean waves for varying the load and/or the value of the inductive (capacitive) element

coupled to the system to resonate with the mechanical converter. The controller may also be used to vary the load to ensure that the value of the load applied to the output of an electric generator may be a continuously varying value which ensures the optimum transfer of power into the load.

BRIEF DESCRIPTION OF THE DRAWINGS

In the accompanying drawing like reference characters denote like components; and

FIGURE 1 is a sketch of a tubular wave energy converter (WEC) system with a piston deployed in a body of water for capturing energy from ocean waves and which may be used to practice the invention;

FIGURES 2 and 2A are cross sections of WECs which may be used to practice the invention;

FIGURE 3 is a simplified schematic diagram of a three-phase generator, driven by a motor contained within a WEC, for the application thereto of an optimum load in accordance with the invention;

FIGURE 4 is a waveform diagram illustrating the heavy modulation of the generator output voltage;

FIGURE 5 is a simplified block diagram of part of a system embodying the invention;

FIGURE 5A is a another block diagram of a system embodying the invention;

FIGURE 6 is a schematic diagram of a rectifier circuit which may be used in systems embodying the invention;

FIGURE 7 is a highly simplified diagram of an inductive element used to resonate with a mechanical to electrical converter exhibiting capacitive characteristics;

FIGURE 8 is an electrical equivalent circuit of a system embodying the invention;

FIGURE 9 is a simplified block diagram of a system embodying the invention;

FIGURE 9A is another block diagram of a system embodying the invention;

FIGURE 9B is a diagram of an inductor network suitable for use in practicing the invention; and

FIGURE 10 is a block diagram illustrating that a wave energy converter (WEC) for use in practicing the invention may be either inductive (LEFF) or capacitive (CEFF).

DETAILED DESCRIPTION OF THE INVENTION

To better explain the invention, reference will first be made to the simplified diagrams of various WEC structures shown in Figs. 1, 2 and 2A.

Figure 1 is a sketch for identifying various relevant dimensional parameters of a system which may be used to practice the invention deployed in a body of water. Figures 2 and 2A are cross-sections of WECs identifying certain of their key elements which are used to practice the invention.

This invention teaches and shows: (a) that various portions of a mechanical, hydraulic, electromechanical and electrical subsystems may be represented by single electrical equivalent circuit which may be used for further development of the system ; (b) the development of a mathematical model to characterize a buoy system, and more particularly, a WEC; (c) a method of extracting electrical power from the WEC; and (d) apparatus and methods to optimize power transfer from the WEC to a load. Thus, the invention resides, in part, in identifying the relationship between a buoy power generation system and the electrical loading on the system. For ease of illustration, in the discussion to follow, reference and assumptions are made which apply specifically to a cylindrically (tubular with piston) shaped WEC of the type shown in Figs. 1, 2 and 2A. However, it should be understood that the invention is applicable to other structures used to convert naturally occurring and recurring forces into electrical energy.

1.0 System Differential Equation

Referring to Figs. 1, 2 and 2A, the basic WEC buoy differential equation is, by balance of forces, given by

$$F_{IN} \sin \omega t = M_{WC} \partial V_P / \partial t + F_C \quad (1)$$

Where:

V_P is the piston velocity;

F_{IN} is the differential force applied to the piston by the ocean wave;

M_{WC} is the mass of the water in the WEC and is equal to the volume of the WEC tube multiplied by the density of water; --Note: that this is a simplification and that, to be more exact, the term M_{WC} should include the mass of other components such as the mass of the tube itself and an "added mass" term used to account for the mass of the water around the WEC being moved. As used herein and in the appended claims the term M_T is meant to include all these masses. However, where M_{WC} is much greater than any other term, the other terms may be omitted when making an approximate calculation.

$M_{WC} \partial V_P / \partial t$ is the acceleration of the water within the buoy; and

F_C is the counter force exerted back on the piston as electrical power is extracted from the load.

This latter term (F_C) is highly significant since it represents the all important electro-mechanical coupling force between generator power extraction and the mechanical motion of the buoy.

Rewriting equation (1) in terms of the system parameters, we obtain in the case of a resistive load

$$\rho g A H \delta / 2 [\sin \omega t] = \rho A L \partial V_P / \partial t + F_C = \rho A L \partial V_P / \partial t + K_G K_T V_P / (R_L r_0^2) \quad (2)$$

where:

ρ = mass density of water,

g = gravity,

A = piston area where, as shown in Fig. 1, the area of the piston is essentially equal to the area of the tube or shell in which it is located. In general, A is equal to the cross sectional area of the shell (tube) when the shell is upright,

H = wave height (peak to trough),

L = length of buoy,

K_G and K_T are the respective voltage and torque constants of the electro-mechanical (EM) generator, and r_0 (in meters of stroke per shaft angular rotation in radians) represents the linear to angular conversion constant of the hydraulic system; and

R_L the generator Δ connected load resistance (**as shown in Fig. 3**).

The parameter δ is derived directly from the solution of the wave equation and represents the fall-off in pressure in the vertical dimension. If δ is defined as a fall-off in pressure the results remain general. Here the results are given for a cylinder. Discarding non linear terms from eq. 2 and assuming the buoy stroke length to be small compared to the length, L , of the buoy the parameter δ is given by

$$\delta = (1 - \cosh(2\pi L/\lambda) + \tanh(2\pi D_W/\lambda) \sinh(2\pi L/\lambda)) \quad (3)$$

where:

λ = to the wavelength of the surface wave; and

D_W is the water depth..

For sinusoidal motion, i.e., regular wave, we can switch to complex notation. Defining $F_{IN} \sin(\omega t) = \rho g A H \delta \sin(\omega t)$ as the effective input forcing function caused by the incoming wave on the piston, and the electro-mechanical coupling constant $K = K_G K_T / r_0^2$, the complex solution for the piston velocity with a resistive load R_L is,

$$V_P = F_{IN} R_L / (K(1 + j\omega\tau)) = V_{PM} / (1 + j\omega\tau) \quad \text{meters/sec} \quad (4)$$

Where:

$$V_{PM} = F_{IN} R_L / K ,$$

$\omega = 2\pi/T$ is the input wave angular frequency,

$$\tau = R_L C_{EFF} \text{ and}$$

$C_{EFF} = MT/K$ is an equivalent capacitance proportional to the mass of the WEC including the water column in the WEC and “added mass” of surrounding water.

For a tall cylinder C_{EFF} is an equivalent capacitance approximately equal to $\rho AL/K = MT / K$.

The recognition that the mass of the WEC including the water column may be characterized as an effective or equivalent capacitance is a significant part of the invention since it provides a basis for calculating the optimum load to be coupled to the system and the value of an inductive element which can be used to resonate with the equivalent capacitance to produce an increase in the transfer of power.

It is seen from (4) that the system dynamics with a resistive load can be represented as a first order low pass filter with a 3 dB point of $\omega_3 = 1/\tau$. It should be pointed out that all mechanical and electrical parameters can be derived from

the solution for piston velocity given in Eq. (4). For a particular system, the corresponding equations for piston stroke S_P , power out P_{out} , and optimum resistive load $(R_L)_{OPT}$ are presented below.

1.1 Stroke:

$$S_P = V_P / j \omega = V_{PM} / (j \omega (1 + j \omega \tau)) \text{ meters} \quad (5)$$

Note: only the real part of equation (5) need be considered.

Optimizing Power Extraction

A significant aspect of this invention is to relate electrical power extraction to the buoy system differential equation and to determine the optimum extraction strategy. Fig. 3 shows the equivalent circuit of an electric generator 42 used in Figs. 2 and 2A. The electric generator is a 3 ϕ generator located within the buoy. (Voltages shown are RMS values.) In Fig. 3, the only voltages externally available are nodes labeled "A", "B", and "C" as the neutral "N" is not brought out. Because of this, power is extracted by Δ connected loads (R_L in the figure) across the 3 line-to-line voltages ($V_{L-L} = \sqrt{3} V_{L-N}$).

1.2 Electrical Output Power (per leg or 1/3 P_T):

$$\begin{aligned} P_{OUT} &= V_{LL}^2 / (2R_L) = K_G^2 \omega_S^2 / (2R_L) = K_G^2 |V_P|^2 / (2 r_0^2 R_L) \\ &= F_{IN}^2 R_L r_0^2 / (2 K_T^2 (1 + \omega^2 R_L^2 C_{EFF}^2)) \end{aligned} \quad (6)$$

1.3 Optimum Load Resistance:

The optimum load resistance is that value of R_L which maximizes the generator power output P_{OUT} . By inspection of Eq. (6), it is seen that P_{OUT} goes

to zero at $R_L = 0$ and ∞ and is positive in between so that an optimum does exist.

By definition, $(R_L)_{OPT}$ is determined by the solution to $\partial(P_{OUT})/\partial(R_L) = 0$.

Performing this operation on (6) gives,

$$(R_L)_{OPT} = 1/(\omega C_{EFF}) \quad (7)$$

The condition (7) is equivalent to $(R_L)_{OPT} C_{EFF} = 1/\omega = T/(2\pi)$. Substituting this into (6) yields the result that the output power is approximately proportional to $H^2 T$ or the efficiency is constant as long as the load value tracks according to (7). (This ignores, for now, the length degradation factor of Eq.(2) which is independent of R_L but falls off significantly with T .)

Substitution of $(R_L)_{OPT}$ into Eq. (6), gives the maximum power available for a general system as: $P_{MAX} = [(\rho g H A \delta)^2 T / (32\pi M T)] [Kg/Kt] \quad (8a)$

for a cylinder P_{MAX} may be expressed as follows:

$$P_{MAX} = \rho g^2 H^2 T A \delta^2 / (32\pi L) \quad (8)$$

where P_{WAVE} is the total available power from the wave incident on a buoy of diameter D and length L , i.e., $P_{WAVE} \approx H^2 T D$ (kW).

The electric generator output voltage waveform may be heavily modulated as shown in Figure 4.

Achieving maximum power transfer requires that the load seen by the generator equals to $(R_L)_{OPT}$. To accomplish this result, a system embodying the invention may be configured as shown in Fig. 5. An hydraulic motor 40 (or any suitable converter) drives an electric generator 42. The output of the electrical generator 42 is supplied to an AC to DC converter 44. The AC to DC converter 44 may be a rectifier circuit of the type shown in Fig. 6. However, it should be

appreciated that any suitable AC to DC converter may be used. The output of the AC-to-DC converter is applied across a storage capacitor C1, which in effect stores the energy captured by the WEC from the ocean waves. Where the voltage across C1 would vary significantly, a DC-to-DC converter (e.g., a switching regulator) may be used to provide a more constant DC voltage to inverter 50. The output of the DC-to-DC converter section is then applied to the power inverter section which is coupled at its output to a power grid 60 which is the ultimate load and goal for which the system is intended. Inverter 50 converts the input DC voltage to a single phase or to a multiphase AC signal which is supplied to the power grid and which must meet the requirements of the grid. However, the power grid represents a variable load which, depending on demand, may range over a wide range of values. This variable load is reflected via the converter-inverter 50 across the storage capacitor C1 and back across the output of the AC to DC converter 44 and via the converter 44 to the electrical generator 42.

As noted above, it is important to maintain the impedance seen by the electrical generator close to the value of R_{LOPT} . In circuits embodying the invention, the condition of the load may be sensed and a signal S5 may be fed to the controller 54 indicative of the load condition. The value of the load may then be calculated by the controller 54. The value of the load impedance may then be controlled by means of a controller 54 which controls the rate at which the inverter is switched. Alternatively, the controller 54 may be used to directly increase or decrease the value of the load by means of a control signal S6.

At the same time, the power available to be distributed is also variable since it depends on wave energy applied to the WEC, which may vary considerably. By way of example, when there is more power available than is required by the load or when the load decreases below a certain level the controller 54 can (via a signal such as S6) be used to switch in storage batteries or other energy absorbing means which can subsequently be used to provide more (or less) power when load conditions change. The controller 54 is also responsive to a signal, identified as S1, from a sensor 56. The sensor 56 may be any sensor capable of indicating and/or determining the power available from the waves and/or the conditions of the WEC system.

Alternatively, sensor 56 may be any sensor capable of signaling to the controller 54 the amount of power available from the electrical generator 42. The controller 54 is pre-programmed to respond to the sensor 56 generated signals S1 to, in turn, generate a signal, or signals, identified as S2, which is fed to the inverter 50 and which controls how much power can be drawn (taken) from the inverter and supplied to the power grid (i.e., the ultimate load).

In addition (or alternatively), the power (voltage and/or current) being generated by generator 42 may be supplied (see dashed lines S1A in Fig. 5) directly to the controller 54. Controller 54 normally has a much faster response time than the ocean wave or the electrical power signal being generated by the ocean wave. The controller 54 may thus act directly in response to the ocean wave input.

Alternatively, the controller 54 may be pre-programmed and loaded with statistical data as to ocean wave and climate conditions so as to control the system response with a view to optimizing the power transfer. The signals S1 (or S1A) and S2 and the controller action on inverter 50 thus effectively control the value of R_L seen by the generator 42 so that the system is operated such that the effective load is made or kept equal to R_{LOPT} . It is significant that, in systems embodying the invention, the available or average input power, as well as the desired optimum load, are factored into the equation to optimize power transfer.

It should be emphasized that a particular rotary hydraulic motor-rotary electrical generator was used for purpose of example and that any other suitable motor generator combination may be used (e.g., a rack and pinion combined with a generator, or a linear electromagnetic generator instead of a hydraulic rotary generator) may be used. Likewise, many different types of converters responsive to naturally recurring sources of energy (for example, a water flow turbine) may be used instead of the WECs shown herein. The cylindrical tube shown in Figs. 1, 2 and 2A are only for purpose of illustration. The invention may be used in any system including any shell (e.g., container, cylinder, cone) of arbitrary shape suitable for containing a volume of water which in combination with a piston like structure can capture the force of the waves and convert that force to a mechanical motion or force which is then converted to electrical energy.

A slightly more detailed and modified version of Fig. 5 is shown in Fig. 5A. Fig. 5A illustrates that the any of the following signals may be applied as inputs

to the controller for indicating certain input power or other operating conditions: (a) rotation speed (ω_m) of the hydraulic motor 40; (b) The frequency (f_G) of the generator 42; (c) the amplitude (V_{AC}) of the generator voltage; and (d) a rectified voltage at the output of a filter 44b. These signals may be in addition to wave sensor signal and other suitable signals (e.g., from CEFF). The controller can then send one or more signals (e.g., S6a, S6b) to a DC-to-AC converter (e.g., an inverter) 50a, a DC-to-DC converter 50b (e.g., a switching regulator) capable of driving a DC load or a regulated DC-to-AC converter (e.g., an inverter) 50c. The controller signals (S6a, S6b) can be used to automatically and/or selectively control the operation of any one of the loads such that the generator 42 "sees" the optimum load, $RL(OPT)$. The controller can also use look up tables preprogrammed into the controller for maintaining $RL(OPT)$; where $RL(OPT)$ is equal to $1/(\omega C_{EFF})$.

EFFICIENCY IMPROVEMENTS WITH ELECTRICALLY RESONANT LOADS:

Applicants recognized that the M_{WC} acceleration term in Eq. (2), above, could be made resonant with an inductive generator load to greatly improve power transfer efficiency. Applicants further demonstrated that each phase of the electrical generator could be loaded with a series resonant circuit and then observed both the electrical and mechanical behavior of the system combination including the WEC, the hydraulic motor and the electric generator. The highly simplified schematic of a particular resonant load is shown in Figure 7.

The electrical resonant frequency of the load circuit shown in Fig. 7 was found to be 48 Hz corresponding to a shaft speed of 16 rps (3 pole pairs in the

generator). The electrical output showed a sharp peak at this frequency but, most important, the mechanical torque applied showed the same sharp peak at the same frequency. In other words, electrical load current produces a counter torque in both magnitude and phase! This means that an electrical component in the generator output loop can, indeed, resonate with a mass of water in the WEC and produce power gain by approaching a unity system power factor. The extent of the improvement is further discussed below.

Efficiency Improvement at Resonance

Therefore, another aspect of Applicants' invention relates to apparatus and methods for controlling the output power delivered to a resistive load when it is inductively tuned at, or near, the dominant wave frequency. This modifies the system differential equation (2) and results in a 2nd order system in velocity which can be modeled by the electrical equivalent circuit of Fig. 8.

In Fig. 8, the current source 80 represents the force applied to the piston of a buoy by ocean waves (1 A=1 N), the capacitance C2, which is equal to **CEFF**, is the mass of the water column (1 F=1 Kg) and the EMT is a mythical (but mathematically correct) Electro-Mechanical Transformer which performs the function of translating the linear motion of the WEC into the rotary motion of the generator via the hydraulic system. The power generation capabilities of electrically resonant systems may now be obtained and examined. The output power as a function of input wave power is

$$P_{out}=I_M^2 R_L/((1-\omega^2 LC_E)^2 + (\omega(R_L+R_W)C_E)^2) \quad (9)$$

where $I_M = k_G K F_{IN} \delta / r_0$ and $F_{IN} = \rho g A H \delta / 2$ are as defined, above, and C_E is equal to C_{EFF} .

P_{out} may be computed for different types of buoys and for different wave conditions. In a particular embodiment the inductor L was chosen to resonate with C_E at the peak of the wave period power spectrum. In systems embodying the invention controls may be included to enable the inductor to be continuously varied, as shown in Fig. 9, below. Also, in the embodiment of Fig. 8, R_L was chosen to be equal to the winding resistance, R_W , of the inductor which maximizes the power at resonance. The available power P_{AV} and output power P_{OUT} (resistive load) and P_{RES} (resonant load) may then be computed.

Figure 9 is a simplified diagram of a system in which the controller 54 controls and changes the actual inductance of inductors (in inverter 50a) connected in series with the load 60 (or perform a mathematically equivalent function) to obtain increased output power and efficiency. In response to the sensor signal $S1$ from sensor 56, controller 54 is preprogrammed to modify an inductance network in inverter 50a, which is similar to inverter 50, but which includes inductors which can be tuned to the load. In this embodiment, as above, the input power may vary as a function of the climate and the load may vary as a function of power demand. However, in both instances, Applicants' invention functions to optimize transfer of power for varying input power conditions and output power demands. That is, a sensor 56 can be used to sense the conditions of the input waves. The controller can be pre-programmed to respond to these conditions on a statistical basis. Alternatively, the controller can

respond directly to the input conditions of sensor 56. Still further, the output conditions of the electrical generator can be fed to the controller, as shown by dashed line S11. Since the wave period is very (extremely) long compared to the response time of the controller 54 (which would normally be used), much computation and processing can be performed while the electrical output of the generator is being sensed.

Fig. 9A is a modified version of Fig. 5A showing the placement of an inductive element 500 between the output of the electric generator 42 and the input to the rectifier section 44a. The inductive element 500 may be an inductor having a fixed value, where the fixed value is selected such that ωL is approximately equal to the average value of $1/(\omega C_{EFF})$. Alternatively, as shown in Fig. 9A, the inductive element 500 may be a variable inductor whose value may be varied by controller 54 as a function of any of the input signals to the controller 54 and/or as a function of any change in the ocean waves causing C_{EFF} to change; with the changes in inductance being such as to maintain ωL approximately equal to $1/(\omega C_{EFF})$.

Alternatively, as shown in Fig. 9B, the inductive element may comprise a number of different valued discrete inductors with switches controlled by controller 54 for determining the amount of inductance inserted in the circuit between the electric generator 42 and the rectifier 44a.

In accordance with the invention the controller can send control signals to any of a number of different loads (e.g., 60a, 60b, 60c) such that the generator 42 sees $R_{L(OPT)}$. Concurrently, the controller 54 can switch into the circuit the

optimum inductance required to achieve resonance as a function of an input (S1) from the wave sensor 56a, or from the CEFF monitor 57 or from any other input to the controller 54. The controller may use a look up function or an algorithm with the frequency of the waves and/or CEFF as independent variables.

Alternatively, the controller 54 can vary the inductance slowly over several wave periods (cycles) during which the system “hunts” for maximum power transfer points. This may be accomplished by periodic computation of power per wave which in turn can make use of a number of different sets of parameters (e.g., Power is equal to voltage times current, or speed times torque, or velocity times force).

Alternatively, the controller may also be used to send signals to an AC to DC converter such that the voltage leads or lags the current and at the same time control the impedance to be approximately equal to $R_{L(OPT)}$. Thus, the effective inductance to resonate with the electromechanical system may be accomplished in a different manner.

In figures 1, 2 and 2A the equivalent impedance is characterized as being capacitive and equal to CEFF. To achieve resonance an inductive element is inserted into the circuit. However, it should be appreciated that the equivalent impedance of a WEC functioning differently than the WECs of Figs. 1, 2 and 2A may be characterized as being inductive and equal to LEFF. For such a WEC, a capacitive component would be inserted in the generator output loop having a value to resonate with LEFF. This is shown in a general manner in Fig. 10, where a resonating network 510 is placed in the power transfer loop. If the output

impedance of the mechanical force to electrical energy converter 42a is characterized as ω_{LEFF} then, the resonating network is controlled and made capacitive such ω_{LEFF} is equal to $1/\omega_{CEFF}$.

Regarding the piston shown in Figs. 1, 2 and 2A, note that the piston may be any inner body component such that its movement within a shell (tube) causes a mechanical, electrical or electromechanical response to be generated .